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Evaluation of brain-computer interfaces in accessing computer and other devices by people with severe motor impairments

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Abstract

A brain-computer interface (BCI) translates brain signals into commands that can be used to control computer applications or external devices. BCI provides a non-muscular communication channel and therefore it assumes a crucial importance for individuals with motor functions severely affected. The evaluation of BCI by individuals with severe disabilities is of utmost importance to understand the BCI feasibility as an assistive technology. This paper summarizes some of the results achieved in our research lab, with different BCIs tested by individuals with severe motor disabilities, focusing on some practical aspects of BCI evaluation, and on the target population.

Keywords: Brain-computer interface (BCI), P300, motor disabilities, assistive technology.

1. Introduction

There is today a wide variety of access technologies for individuals with severe motor disabilities such as mechanical switches, proximity sensors, adapted joysticks, voice recognition, head-trackers, eye-trackers, electromyography (EMG), elecotrooculography (EOG) and electroencephalography (EEG) (see a generic survey in [1]). In some degenerative neuromotor diseases such as amyotrophic lateral sclerosis (ALS), patients enter progressively in a locked-in state (LIS), with only residual voluntary control, such as eye movement and blinks. In the end stage of the disease, patients may lose all motor control entering in a complete locked-in state (CLIS) [2]. For these individuals, brain-computer interfaces (BCIs) emerge as a potential solution in order to

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restore communication. BCI only requires brain signals to translate user's volitional intents into commands, and therefore, provides a non-muscular communication channel which can be used by completely paralyzed individuals [3]. BCIs based on electrophysiological signals can be classified according to their degree of recording invasiveness, ranging from non-invasive (scalp EEG recording), medium-invasive (Electrocorticography (ECoG) recording), and highly invasive (intracortical recording). Despite the great quality of the signals of invasive approaches (ECoG and intracortical), and their success in terms of high bandwidth and multi-dimensional control, experiments with ECoG-BCIs have been made mainly in patients with epilepsy who undergo the temporary placement of electrodes for monitoring and localization of seizure foci prior to surgical procedure [4], and intracortical-BCIs experiences have been reported mainly in non-human primates [5, 6]. The risks associated with long-term recordings and other practical issues strongly limit the use of these techniques. Thus, BCI based on scalp recorded EEG still remains the most widely used approach, requiring relatively low cost devices. EEG-based BCI will be the topic of the remaining of this paper.

Although most non-invasive brain-computer interfaces have been tested in healthy subjects, there has been over the last decade a growing number of studies reporting successful experiences with people with severe motor disabilities [2, 7-18]. Clinical evaluation is of utmost importance to assess the real feasibility of BCI. Research in clinical contexts has been focused mainly on the restoration of communication, in the form of mental typewriters (speller systems), but many other BCI applications are increasingly deserving more attention, namely, control of robotic devices (e.g., wheelchairs, manipulators), environment control in ambient assisted living, neuroprosthetics, neurorehabilitation, neurotherapy and gaming (see a survey in [19]).

Several BCI systems have already been developed at our research lab, ranging from speller systems [18, 20, 21], interfaces designed to steer a robotic wheelchair [22, 23], and BCI games with potential application as a neurotherapy tool for behavioural disorders [24], but not all have been tested clinically. This paper summarizes some of the results of the assessment of BCI by people with severe disabilities, namely, ALS, Duchenne muscular dystrophy (DMD), spinal cord injury (SCI) and cerebral palsy (CP) [20, 18], and draws conclusions regarding the practical application and suitability of BCI. Particular focus is given to the CP group because they have not been included in many studies with BCI experiments.

2. Background

2.1. Neurophysiology

There are currently three major neuromechanisms to control EEG-based BCIs: control of sensorimotor rhythms (SMR), visual evoked potentials (VEP) and P300 event-related potentials (ERP). In the SMR approach, users learn to control sensorimotor rhythms by performing mental tasks, such as motor imagination (e.g., imagination of hand movement). The main neurophysiologic features are related to the desynchronization and synchronization (ERD/ERS) of sensorimotor rhythms μ (8-12 Hz) and β (18-25 Hz) [25]. In the VEP approach, BCI is controlled by a neurophysiologic response to some type of visual stimulus. Most of the studies are based on steady state visual evoked potentials (SSVEP), which are potentials evoked at the visual cortex as response to stimuli flickering at rates above 6 Hz [26]. The P300-based approach relies on the response to an infrequent event occurring randomly within frequent standard events (oddball paradigm) [27]. From these three approaches, SSVEP is the one presenting the highest transfer rates. However, because most of these systems rely on precise eye gaze, this technique has been discarded of clinical experiments, arguing that eye-trackers can be used instead. A SMR-BCI can provide a continuous control and does not require any type of stimuli. However, users need long periods of training to learn to control their rhythms, which significantly limits its clinical application, particularly in locked-in patients. P300-BCIs require some type of stimuli (visual, auditory, tactile), and the user can only issue a command in fixed intervals of time. Nevertheless, its use requires a short training/calibration time, and it typically presents a higher transfer rate than SMR-BCI. Thus, P300-based BCI has favorable characteristics for clinical use, and therefore was the chosen approach.

The P300 ERP is a positive deflection occurring about 300 ms after the onset of a target stimulus, as shown in Fig. 2. To elicit a P300, it is required to design an oddball paradigm, which consists of two types of events: rare and common. The rare event (target) occurs randomly among the common events (standard). A description of the tasks is given in section 3.2.

2.2. Generic view of a BCI

Fig. 1 shows a generic representation of a non-invasive BCI system. EEG signals are recorded from the surface of the scalp, amplified by a bio-amplifier, converted to digital, and then processed and classified in real-time. Signals are then translated into control commands, which result in actions that provide a feedback (visual, auditory or tactile) to the user.

2.3. EEG recording

The EEG activity can be recorded from the scalp using several types of electrodes. At the present time, most of the systems uses passive and active electrodes with gel preparation. Dry electrodes are emerging in the market, which have the advantage of providing a fast setup without gel preparation. The experiments performed in our research lab have been made with Au and Ag/Cl passive electrodes. We have limited the number of electrodes to 12, in order to provide a feasible system. Fig. 3d) shows the cap, electrodes at positions Fz, Cz, C3, C4, CPz, Pz, P3, P4, PO7, PO8, POz and Oz according to the extended international 10-20 standard system, and the gUSBamp bio-amplifier system (g.tec, Inc.).

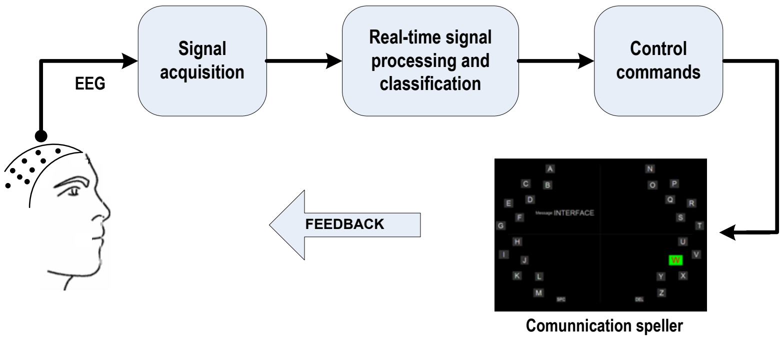

Fig. 1. Generic representation of a BCI system.

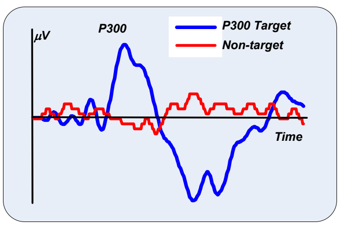

Fig. 2. Typical P300 waveform elicited by a target event in an oddball paradigm.

3. Experiments

The BCIs were tested by individuals with CP, DMD and SCI recruited from the center of the Association of Cerebral Palsy of Coimbra (APCC), and individuals with ALS recruited from the Hospitals of the University of Coimbra (HUC).

3.1. Characterization and selection of patients to BCI experiments

A summary of the characteristics of the participants is described in Table 1. A brief description of the motor disorders is given to understand the potential importance of BCI for individuals with these disorders. Cerebral palsy is a non-progressive neurological disorder resulting from a brain injury that occurs before cerebral development is complete [28]. It is generically characterized by abnormal movements and posture usually accompanied by dysarthria, and it is usually divided in three groups: spastic, dyskinetic and ataxic [29]. The symptoms and levels of functionality vary significantly among patients, ranging from severe cases, in which there is a complete lack of movement control accompanied with cognitive impairments, intermediate cases in which patients have a coarse control of one member, and mild cases in which patients can have a high level of autonomy with a minimum assistive help. Given the broad range of levels of functionality of this group, some criteria were taken into consideration to select the participants for BCI experiments. The selection included only:

- Individuals with normal cognitive levels, i.e., able to read, write and count;
- Individuals who could benefit from a BCI interface, i.e., users with severe limitations of communication and mobility. That includes users who already use interface devices in the daily life, but for which BCI could be a potential alternative, and users that are unable to control existing standard interfaces;
- Individuals with no constraints for setup montage (electrodes, cap);
- Individuals with normal visual acuity.

Four of the five CP participants (S1-S4) are confined to a wheelchair and are highly dependent of human assistance. Nevertheless, all of them have coarse control in one of the limbs or head. This gives them the ability to control, even with great effort, adapted interfaces in order to command the wheelchair and to access the computer. Participant S5, with ataxic form of CP, can walk, but her high motor incoordination strongly hampers the access to the computer. DMD is a genetic disorder caused by a single gene mutation. Children and adolescents with DMD evidence a progressive muscular weakness affecting all voluntary muscles and often exhibit cognitive deficits. Usually by the ages of 12, children lose the ability to walk and are wheelchair dependent. In later stages, DMD affects heart and respiratory muscles, and thus patients require artificial ventilation and other types of support. Participant S6 with DMD is confined to a wheelchair but is unable to control it. This participant has only residual movements of the head and recently lost the ability to control an head-tracker. The participant S7 with SCI has a tetraplegia, but can use the head to control the wheelchair and access the computer. ALS results in a progressive degeneration of motor neurons that leads to progressive weakness and atrophy of all voluntary muscles. The group of individuals with ALS, S8-S14, is still in early to intermediate levels of the disease, and thus, they did not require any type of assistive technology at the time of the experiments. This disease may have a very rapid progression, so it is important to get start the tests before patients enter in severe conditions. The main signs of participants were dysarthria, dysphagia, and muscular weakness in limbs.

Table 1. Characteristics of patients.

Subject	Age	Diagnosis	Mobility / Interface	Computer / Interface	Speech
S1/F	18	CP	Electric wheelchair / HSS	Yes / HS and HT	Hardly intelligible
S2/M	34	CP	Electric wheelchair / JF	Yes / MF	Hardly intelligible
S3/M	46	CP and distal hernia	Electric wheelchair / JC	Yes / HT	Hardly intelligible
S4/M	45	CP	Manual wheelchair / Foot	Yes / HPD	Hardly intelligible
S5/F	42	CP	Uncoordinated march / -	Yes / GK and TB	Hardly intelligible
S6/M	30	DMD	Manual wheelchair / no control	Yes / HT	Weak affected by tracheotomy
S7/M	28	SCI (C3-C4)	Electric wheelchair / JC	Yes / HT	Normal
S8/F	67	ALS (Bulbar-onset)	- / -	- / -	Hardly intelligible
S9/F	75	ALS (Bulbar-onset)	- / -	- / -	Hardly intelligible
S10/M	58	ALS (Bulbar-onset)	- / -	- / -	Intelligible
S11/F	78	ALS (Spinal-onset)	Manual wheelchair / -	- /-	Hardly intelligible
S12/M	80	ALS (Bulbar-onset)	- /-	- /-	Intelligible
S13/M	66	ALS (Spinal-onset)	Crutch / -	- / -	Intelligible
S14/M	78	ALS (Spinal-onset)	- / -	- / -	Intelligible

HSS: head scanning-switch; HT: head-tracker; JF: joystick-foot; JC: joystick-chin; HPD: head-pointing device; MF: mouse-foot; GK: grid-keyboard; TB: track-ball.

3.2. BCI systems and procedures

As already referred, the BCIs were based on the P300 neural mechanism, evoked by oddball paradigms. Using the visual modality, the design of the paradigm consists of a set of symbols flashing randomly. A symbol mentally selected by the user is the target event and all other symbols are the standard (non-target) events. Naturally, the target event has always a lower probability than the standard events. The perception of a target event by the user is supposed to elicit a P300 ERP. Since the flashes occur randomly and very fast (the time between consecutive flashes typically ranges from 100 ms to 200 ms), user's spatial and temporal attention is essential to detect the flashing moment. The classification system uses time windows of recorded EEG, which are synchronously labeled with the respective event ID. The P300 ERP has a low signal-to-noise ratio and therefore, several P300s of the same target event have to be combined so that it can be detected by the classification system. This means that the target detection occurs only after a given number of rounds of flashing events, which depends on user's performance. To help the user to increase his/her attention level, the user is asked to mentally count the number of times that the target symbol flashes. The P300 waveform has a high variability between individuals, and also within the same individual over different sessions. Therefore, before the control of the BCI, a calibration of the system is required to adjust the classification models to the user. In our systems, the calibration usually takes less than 5 min. This calibration should not be confused with the training process in SMR-BCIs, in which the user has to train to learn how to control their SMR. The training is usually accompanied with visual feedback, which reinforces learning, and thereby SMR control usually increases with period of training. In P300-BCIs, the user can only improve the strategy to increase his perception to target events, but there is not actually learning over time.

The following visual paradigms were tested with individuals with motor disabilities: row-column (RC) speller [27, 20] (Fig. 3a)), lateral single character (LSC) speller [18] (Fig. 3b)), and Arrow-paradigm [23] (Fig.

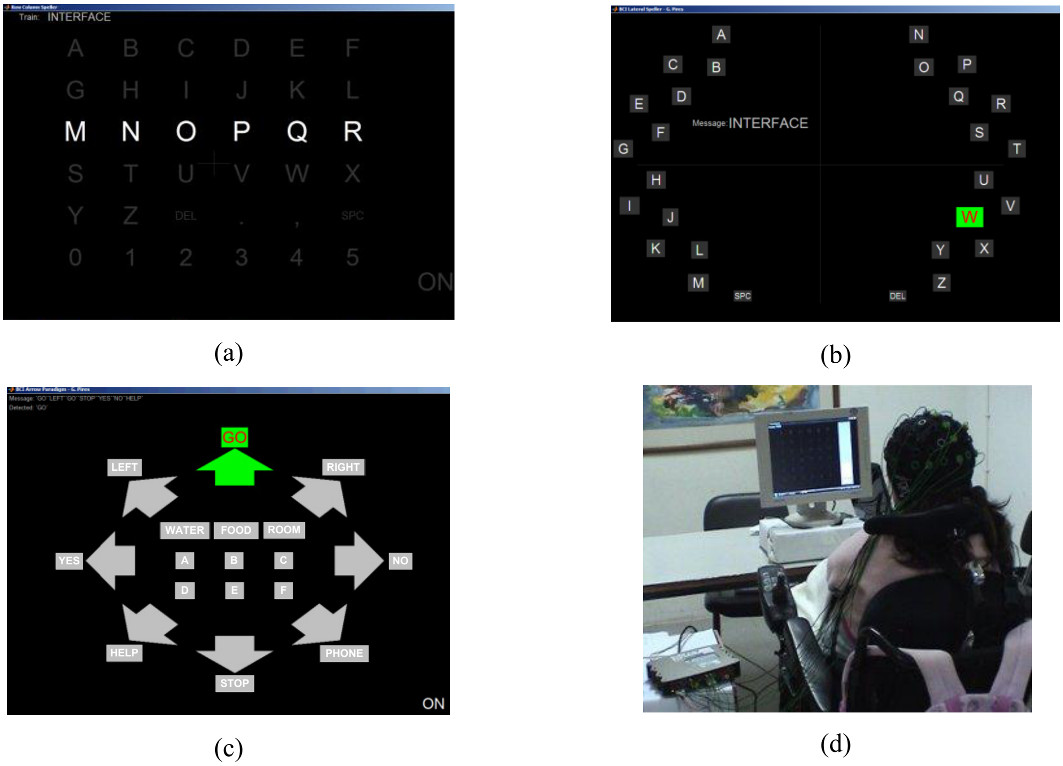

Fig. 3. (a) Screenshot of the RC speller; (b) Screenshot of the LSC speller; (c) Screenshot of the Arrow paradigm; (d) Photo taken at APCC during an experimental session.

3c)). In these BCIs, users can only provide commands in fixed intervals of time, being the time interval dependent of user's performance.

3.2.1. Row-column speller

The RC speller is similar to the one introduced by Farwell and Donchin [27]. The rows and columns flash randomly. The desired letter/symbol corresponds to the intersection of the target row and the target column. A P300 is evoked by the respective flashing row and column. The user writes by selecting sequentially the desired letters. The paradigm comprises all letters of the alphabet, 'space' and 'del' symbols, which allows the user to write words and correct errors when necessary.

3.2.2. Lateral single-character speller

The underlying concept of the LSC speller is similar to RC, but here each letter/symbol flashes individually. The design of this paradigm overcomes some limitations of the RC speller as described in [18]. The user writes by selecting sequentially the desired letters. The paradigm comprises all letters of the alphabet, 'space' and 'del' symbols, which allows the user to write words and correct errors when necessary.

3.2.3. Arrow paradigm

The Arrow paradigm [23] was designed to issue commands to steer a wheelchair (RobChair prototype). The user may select desired directions for local navigation or select final destinations, and may also establish a basic communication with the navigation module or with the human assistant through 'yes' and 'no' words. Due to practical constraints, regarding safety and comfort, patients who tested this paradigm were not seated on RobChair. Some of them controlled RobChair remotely, and others controlled the BCI without moving the wheelchair. Nevertheless, several able-bodied participants steered RobChair on the road [22] achieving performances very similar to those obtained outside the wheelchair, which may be indicative that results with disabled participants could also be similar. It should be emphasized that the control of a wheelchair with BCI strongly depends on a robust navigation system.

4. Results

The initial BCI tests were made with the RC speller and the LSC speller. After the calibration session, participants, seated at their own wheelchair or in a regular chair, were asked to spell the sentence "ESTOU-A-ESCREVER". The number of repetitions (N_{rep}) of the target event was selected according to the offline results from data gathered in the calibration session, and then adjusted according to online performance. A resumed version of the online results is presented in Table 2. The performance was measured in symbols per minute (SPM), number of repetitions (N_{rep}), accuracy (P_{ac}) and the information transfer rate (*ITR*) in bits per minute (bpm) [30]. The Arrow paradigm was tested by 4 participants. The task consisted in detecting a sequence of 15 symbols/commands. The results are presented in Table 3.

Table 2. Online results of participants with CP, DMD, SCI and ALS and performance with non-EEG interfaces. Performances were obtained for spelling a 16 character sentence.

	RC speller			LSC speller			Non-EEG interface
Subject	SPM	P_{ac} (%)	ITR (bpm)	SPM	P_{ac} (%)	ITR (bpm)	SPM
S1	3.35	100.0	17.32	2.95	94.75	12.33	HSS: 6.8
S2	(a)	-	-	(a)	-	-	MF: 43.2
S3	3.35	93.37	15.12	3.72	50.00	5.32	HT: 9.6
S4	(a)	-	-	(a)	-	-	HPD: 51.4
S5	(a)	-	-	(a)	-	-	KG: 31.7
S6	3.87	75.00	11.90	4.28	87.50	15.72	HT: 0.0
S7	2.64	73.33	7.83	3.29	62.50	6.82	HT: 7.2
S8	3.87	100.0	20.01	6.12	87.50	22.46	(b)
S9	5.60	87.50	22.34	5.04	100.0	24.23	(b)
S10	2.95	93.75	13.33	3.29	93.75	13.75	(b)
S11	2.95	100.0	15.28	3.29	43.75	3.77	(b)
S12	(a)	-	-	(a)	-	-	(b)
S13	5.60	87.50	22.34	6.12	93.75	25.54	(b)
S14	3.87	81.25	13.59	4.28	81.25	13.79	(b)

HSS: head scanning-switch; HT: head-tracker; MF: mouse-foot; HPD: head-pointing device; MF: mouse-foot; GK: grid-keyboard.(a): not able to control; (b): not tested;

Table 3. Online results of Arrow-paradigm. Detection of a 15 symbol/command sequence.

	Arrow-paradigm		
Subject	N_{rep}	P_{ac} (%)	SPM
S2	(a)	-	-
S3	5	80%	4.95
S6	5	87%	4.95
S7	6	87%	4.27

(a): not able to control;

From the fourteen participants, ten were able to use BCI effectively. From the participants unable to control BCI, three were from the CP group and one from the ALS group. These participants did not elicit a P300 component or elicited a very weak P300 which was insufficient for online operation of the system. The uncoordinated movements of participant S5 caused high muscular artifacts strongly affecting EEG. The three CP participants unable to control BCI used their regular non-EEG interfaces quite efficiently, while the other two CP used their regular interfaces with much more moderate rates. Still, the SPMs were higher than those obtained with BCI. Particular focus should be given to the participant with DMD, who was unable to use the head-tracker, but had good performances with BCI.

5. Discussion and conclusions

Taking into consideration the performance results, the neurophysiologic analysis, questionnaires and the time spent with the participants, we can synthesize the following conclusions referring positive and negative points:

- The overall results show that BCI can be used effectively by individuals with severe motor disabilities;
- BCI was well accepted by most of the participants;
- BCI experiments were performed in regular environments, similar to domestic ones, showing that it can be used in real-world scenarios;
- Particularly, the ALS group had BCI performances just slightly below those obtained by able-bodied participants [18];
- In one case, BCI showed to be an alternative to a standard interface. The participant with DMD used BCI more efficiently than the head-tracker;
- Only two individuals with CP effectively controlled the P300-based BCI;
- From the universe of cerebral palsy users of the APCC, just a small number fitted the characteristics for potential BCI use. Just a few satisfied the selection criteria initially established in section 3.1;
- Participants able to control some part of the body (e.g., head, foot, chin) with some dexterity, could use non-EEG interfaces more efficiently than BCI;
- A P300-based BCI is an attention task that can be affected by environment distractions, fatigue, pain, involuntary movements, etc. Long periods of BCI revealed fatigue symptoms and a decrease in performance. Moreover, several CP participants had symptoms of pain during the experimental sessions. In some cases it was clear that these symptoms affected their attention;
- Some CP participants used to control very effectively their standard interfaces demonstrated low levels of motivation in BCI experiments;

Several practical aspects of BCI are still very limitative: low transfer rates, requirement of a calibration session, and lack of self-paced automatic control (e.g. automatic switch on/off paced by the user). These are some of the great challenges of BCI and are currently under investigation. The overall results give good indications for the assessment of BCI by individuals with motor impairments. For individuals unable to operate any standard interface, BCI will be the ultimate chance to them to have a communication channel open with the world, allowing them accessing computers, domestic devices and robotic devices.

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